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JUN 81 W J STRONGE, O E HEIMDAHL
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Stress in Single Lap Joints of Dissimilar Materials

by
W. J. Stronge
and
D. E. R. [illegible]
Research Department

JUNE 1981

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FOREWORD

This investigation of single lap joints was conducted as part of an Independent Research program in nonlinear mechanics that supports explosive ordnance design analysis at the Naval Weapons Center. The work was conducted intermittently between 1979 and 1980 under the support of the Director of Navy Laboratories, and was funded by Task ZR000101, DN082080.

This report has been prepared for timely presentation of information. Because of the continuing nature of the research, it is possible that the results may be further extended.

Approved by
E. B. ROYCE, *Head*
Research Department
12 June 1981

Under authority of
W. B. HAFF
Capt., U.S. Navy
Commander

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(U) *Stress in Single Lap Joints of Dissimilar Materials*, by W. J. Stronge and O. E. R. Heimdahl. China Lake, Calif., June 1981, 18 pp. (NWC TP 6264, publication UNCLASSIFIED.)

(U) Two overlapping, semi-infinite plates may be joined by a thin adhesive bond. The stresses in these joints when the plates are loaded in tension are of interest for determining joint strength. A two-dimensional, plane strain, finite element analysis of bonded lap joints between dissimilar plates has been performed. The analysis includes stretching and bending of the plates and rotation of the joint. The stress distributions obtained for the lap joint depend on the elastic moduli and Poisson ratios of the adherends, and on the ratio of relative thickness of the plates to bond length.

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INTRODUCTION

Adhesively bonded single lap joints are frequently used to join plates that are dissimilar in thickness or elastic properties. This investigation is concerned with the strength and mode of failure of a structural lap joint. A plane strain, finite element elastic analysis is used to determine the bond stress between isotropic plates with differing thickness, elastic modulus, and Poisson's ratio.

In a single lap joint, the bond stress has shear and tearing (normal) components. Adhesive shear stress in structural joints is not uniformly distributed; it is heavily concentrated near the ends of the joint. This effect becomes more pronounced as the thickness of the adhesive layer decreases and as bending stiffness of the plates (adherends) increases. In plates that do not bend, Erdogan and Ratwani showed that if adhesive thickness approaches zero, the shear stress at the ends of the bondline becomes large without bound, while between the ends, shear stress approaches zero.[1] In another limit, as in-plane stiffness becomes very small in comparison with bending stiffness, the entire tension force in the plate is transmitted through stress singularities at the ends of the bondline.[2] When two dimensional deformations are permitted, strain variations through the plate thickness diffuse the shear stress concentrations. Still the maximum shear stress occurs within a distance of one adhesive layer thickness of the end of the bondline.

The other adhesive stress component, tearing stress, is a frequently neglected but significant factor in joint strength. It was first analyzed by Goland and Reissner for the case of similar plates.[3] The source of this stress component is the asymmetric joint geometry. Tearing stresses on the bondline enforce displacement compatibility in bending between adherends within the region of the joint. Goland and Reissner showed that the largest tearing stress is near the end of the bondline, and its magnitude can be larger than the shear stress. The concentration of both shear and tearing stress near the ends of the bondline makes structural lap joint strength insensitive to lap length [Kendall].[4]

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[1] F. Erdogan and M. Ratwani. "Stress Distribution in Bonded Joints," *J. Composite Mater.*, Vol. 5 (1971), pp. 378-393.

[2] J. N. Goodier and C. S. Hsu. "Transmission of Tension From a Bar to a Plate," *J. Appl. Mech.*, Vol. 21, No. 2 (1954), pp. 147-150.

[3] M. Goland and E. Reissner. "The Stresses in Cemented Joints," *J. Appl. Mech.*, Vol. 11 (1944), pp. A17-A27.

[4] K. Kendall. "Crack Propagation in Lap Shear Joints," *J. Phys. D: Appl. Phys.*, Vol. 8 (1975), pp. 512-522.

Previous investigations of joint stresses with dissimilar adherends have considered membrane rather than plate models; hence, adhesive tearing stresses were not determined.[1,4,5] Other analyses have developed the equations for dissimilar plates that include bending but have not explored the effects of adherend dissimilarities.[6] In this investigation, shear and tearing stress concentration factors at the end of the bondline are determined. The adherend in-plane stress concentration factor is also obtained so that adherend and adhesive fracture of particular materials can be compared.

ANALYTICAL MODEL

Analytical investigations of adhesive lap joints may be divided into two classes depending on the thickness, t, and elastic modulus, E, of the adhesive compared with those of the adherends. In joints with relatively flexible adhesive layers ($t_a/E_a > t/10E$), the stresses are almost uniformly distributed along the length of the joint.* In joints with relatively stiff adhesive layers ($t/E > t_a/10E_a$), the adhesive shear stress depends on the strain variation along the bondline within each adherend. The latter are known as structural joints.

There are large stress concentrations near the ends of structural joints. The dependence of the stress concentrations on adhesive thickness and the ratio of the elastic moduli has been illustrated by Wosley and Carver for similar adherends.[7] Even when plate bending is included, the adhesive stress concentrations become large without bound as adhesive thickness approaches zero. (In the case of similar materials, England has shown this stress singularity to be of order $r^{-.58}$ where r is the distance from the end of the bondline.[8]) This investigation uses a finite element analysis to determine a value for the stress concentration in the limiting case of zero adhesive thickness where displacements and tractions across the bondline are continuous. This value is obtained

---

* The subscript a refers to the adhesive.

[5] Eli Sternberg. "Load-Transfer and Load-Diffusion in Elastostatics," in *Proceedings of the Sixth U.S. National Congress of Applied Mechanics, Cambridge, Mass., 15-19 June 1970*. New York, American Society of Mechanical Engineers, 1970. Pp. 34-61.

[6] W. J. Renton and J. R. Vinson. "Analysis of Adhesively Bonded Joints Between Panels of Composite Materials," *J. Appl. Mech.*, Vol. 44, Series E, No. 1 (March 1977), pp. 101-106.

[7] G. R. Wosley and D. R. Carver. "Stress Concentration Factors for Bonded Lap Joints," *J. Aircraft*, Vol. 8, No. 10 (1971), pp. 817-820.

[8] A. H. England. "On Stress Singularities in Linear Elasticity," *Int. J. Engr. Sci.*, Vol. 9 (1971), pp. 571-585.

by extrapolation from nearby elements. It has significance for materials where plasticity or other nonlinear effects limit stress magnitudes. The structural single lap joint configuration analyzed is illustrated in Figure 1.

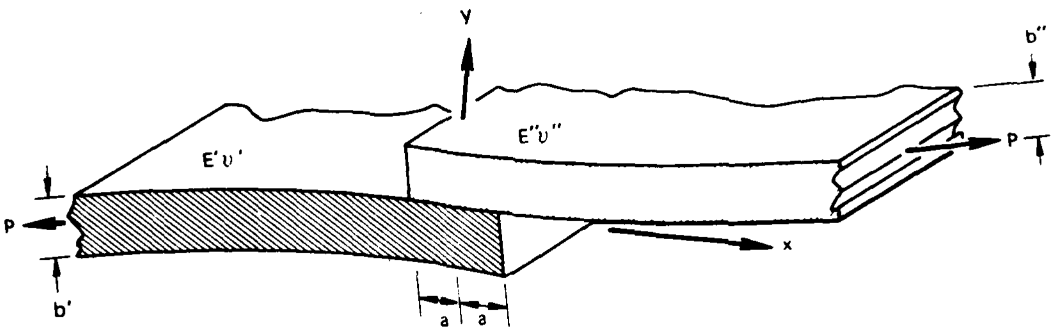

FIGURE 1. Lap Joint Geometry.

A finite element model of the lap joint was developed from four-node quadrilateral elements. The model (Figure 2) contains 308 elements and 391 nodes. These were arranged with decreasing mesh size near the ends of the bondline where the largest and most rapid change in stress was anticipated. A static analysis of this model was conducted by the general purpose structural analysis program, ADINA.

The particular parametric values used in this study were $a = 1$, $L = 6$, $E' = 10^5$, $\nu' = 0.32$, and $P/E' = 1$. The effect of dissimilar adherends and varying joint ratios was investigated by letting $E''/E' = 1, 2, 5, 10$; $b' = b'' = 0.25, 0.5$, and 1.0; $\nu'' = 0.32$ and 0.48.

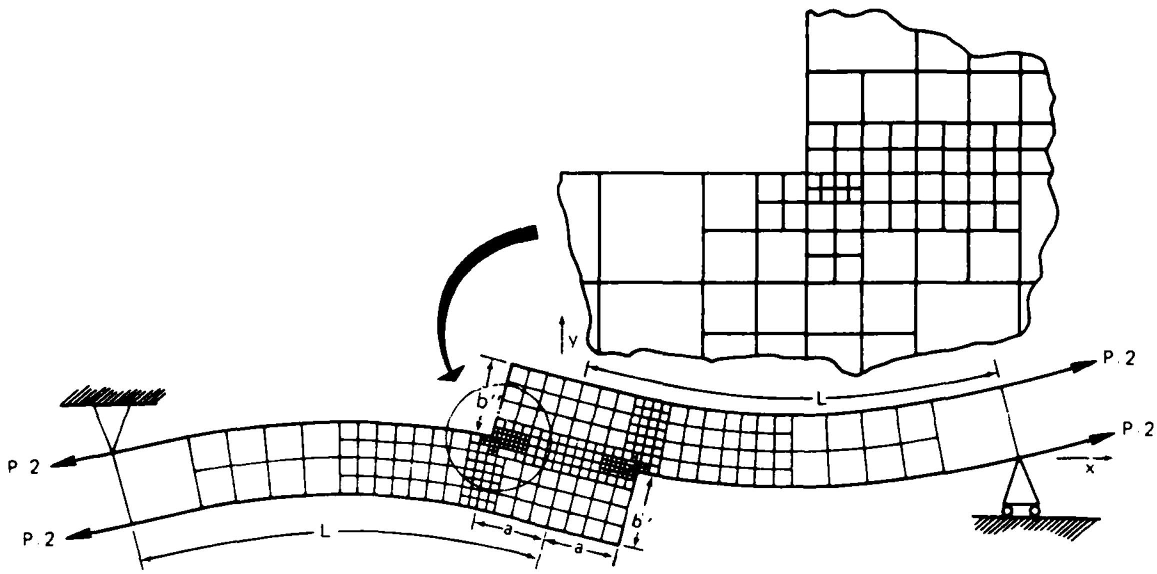

FIGURE 2. Lap Joint Finite Element Model.

DISCUSSION OF RESULTS: BONDLINE STRESS DISTRIBUTION

The adhesive stress distributions in structural lap joints are concentrated toward the ends of the bondline. In Figure 3, shear and normal bond stress distributions for a joint with similar adherends are shown for three overlap-to-thickness ratios. These distributions are indistinguishable from analytical results of Chang and Muki.[9] Typically, inside the ends of the bondline the shear stress rapidly approaches a small positive value while the normal stress swings first to compressive values and then vanishes at the center.

When joints between adherends with differing elastic moduli are analyzed, the stress distributions are skewed toward the end of the stiffer adherend (see Figure 4). This skewed shear stress distribution results from the requirement for extensional displacement compatibility between two plates of differing stiffness. The amount of shift can be obtained by considering a membrane analysis of two plates with elastic

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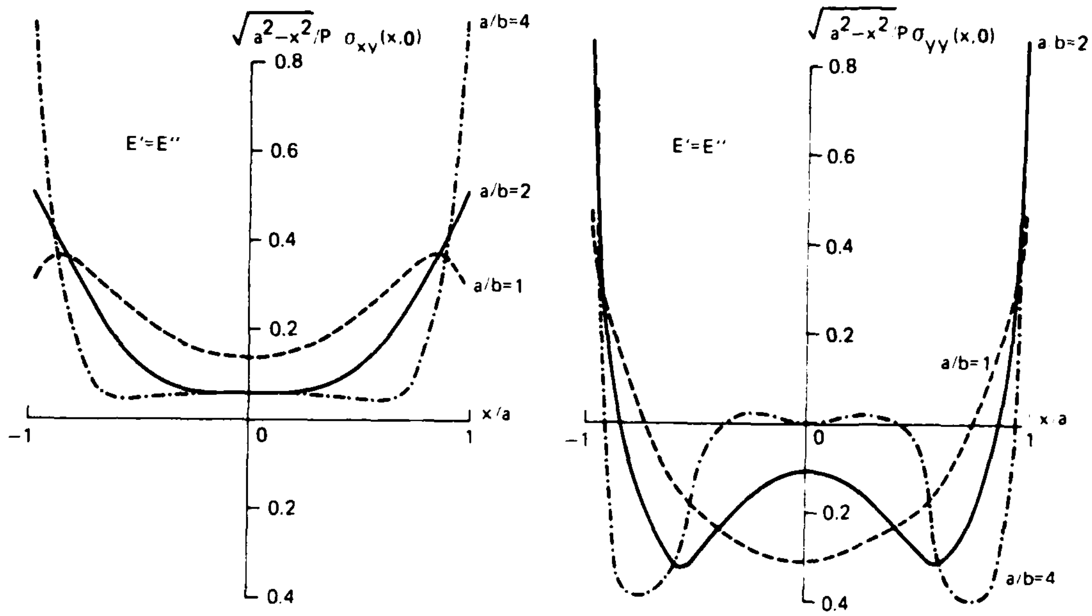
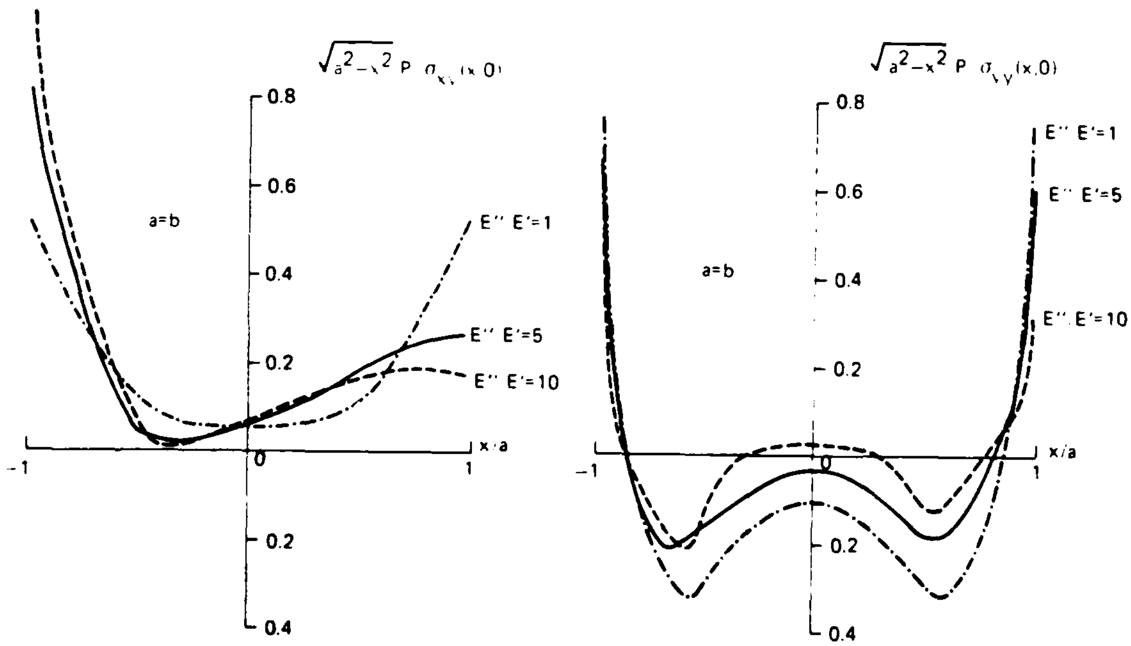
[9] D. J. Chang and R. Muki. "Stress Distribution in a Lap Joint Under Tension-Shear," *Int. J. Solids Structures*, Vol. 10 (1974), pp. 503-517.



(a) Shear stress (b) Normal stress

FIGURE 3. Lap Joints of Similar Materials.



(a) Shear stress (b) Normal stress

FIGURE 4. Lap Joints of Dissimilar Materials.

moduli E', E'', and thickness t', t'' subjected to a tension force P per unit length along the joint. In a membrane analysis, the entire force will be transmitted through shear forces at the ends of the bondline. These forces are

$$\tau' = P/(1 + t''E''/t'E') \tag{1a}$$

$$\tau'' = Pt''E''/t'E'(1 + t''E''/t'E') \tag{1b}$$

where τ^i is the shear force per unit joint length at the edge of the ith plate. The results of the two dimensional analysis shown in Figure 4 have a less pronounced shift than this membrane analysis predicts. When adherends of different thickness are considered, the shift in stress distribution toward the end of the stiffer adherend is even smaller than that obtained with differing elastic moduli.

DISCUSSION OF RESULTS: ADHEREND STRESS DISTRIBUTION

Adherend stresses outside the region of the joint are a simple combination of plate tension and bending. The bending arises from the asymmetric joint configuration and, near the joint, it more than doubles the in-plane stress on the bond side of the plate.

At the ends of the joint, in-plane stresses due to bending change radically since, in a structural joint, the two plates act as a single laminated beam. The bending moment about the discontinuous neutral axis of this discontinuous beam is

$$M(x) = \begin{cases} (1 + x/L)P(t' + t'')/4 & L \leqslant x \leqslant -a \\ -(\eta - x/L)P(t' + t'')/4 & -a < x < a \\ (1 - x/L)P(t' + t'')/4 & a \leqslant x \leqslant L \end{cases} \tag{2}$$

where $\eta = (1 - \alpha\beta^2)/(1 + \alpha\beta)$, $\alpha = E'/E''$, and $\beta = t'/t''$.

The slope of the moment function is determined by the load offset. This slope will be small if the adherend-to-joint-length ratio, L/a, is large. The moment of inertia of the three beam segments about their respective neutral axes will be

$$I = \begin{cases} (t')^3/12 & -L \leqslant x \leqslant -a \\ [(t'')^3/12](1 + \beta)\gamma/(\eta + \beta) & -a < x < a \\ (t'')^3/12 & a \leqslant x \leqslant L \end{cases} \tag{3}$$

where $\gamma = 4\beta + 4(1 - \beta)\eta - 3\eta^2$.

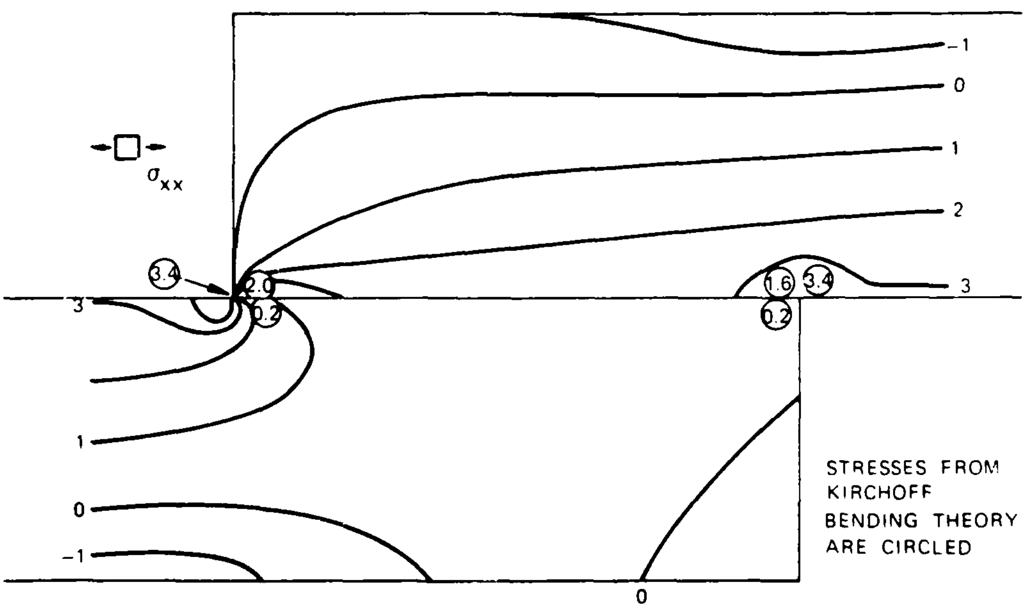
The distance from the neutral axis to the bondline is

$$c = \begin{cases} b'/2, & -L \leqslant x \leqslant -a \\ b''\eta/2, & -a < x < a, \quad y > 0 \\ b''\alpha\eta/2, & -a < x < a, \quad y < 0 \\ b''/2, & a \leqslant x \leqslant L \end{cases} \tag{4}$$

Consequently, in-plane stresses at the ends of the bondline due to combined tension and bending will be

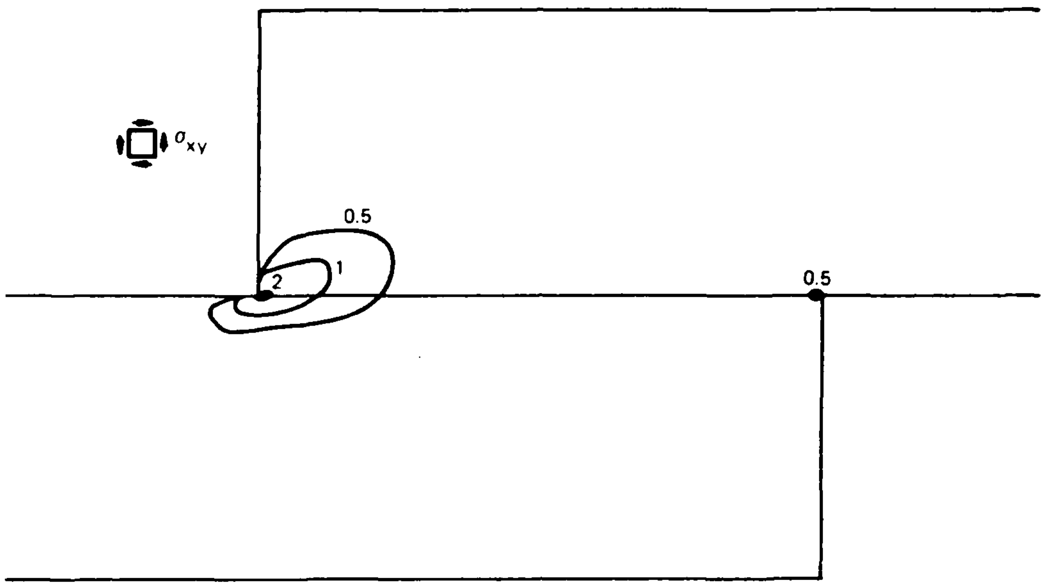
$$\begin{aligned} \sigma_{xx}(-a^-,0^-) &= (P/b')\,[1 + 3(1 + 1/B)(1 - a/L)/2] \\ \sigma_{xx}(-a^+,0^-) &= (P/b')\,[\alpha B/(1 + \alpha B) + 3(\eta + a/L)(1 - \eta)/2\gamma] \\ \sigma_{xx}(-a^+,0^+) &= (P/b'')\,[1/(1 + \alpha B) + 3(\eta + a/L)(\eta + B)(\eta)/2\gamma] \\ \sigma_{xx}(a^-,0^-) &= (P/b')\,[\alpha B/(1 + \alpha B) + 3(\eta - a/L)(\eta + B)(1 - \eta)/2\gamma] \\ \sigma_{xx}(a^-,0^+) &= (P/b'')\,[1/(1 + \alpha B) + 3(\eta - a/L)(\eta + B)\eta/2\gamma] \\ \sigma_{xx}(a^+,0^+) &= (P/b'')\,[1 + 3(1 + B)(1 - a/L)/2] \end{aligned} \tag{5}$$

Figure 5 illustrates a stress distribution for a joint between differing elastic modulus materials, $E''/E' = 10$. In Figure 5a, contours of equal adherend in-plane stress are shown. The respective Kirchoff plate stresses are indicated for comparison.

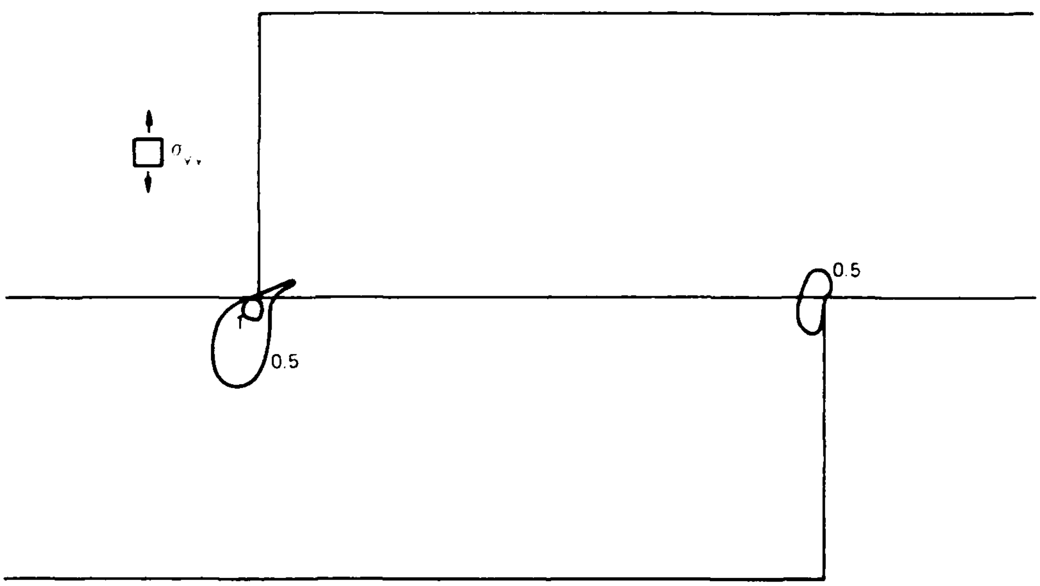


(a) In-plane stress

FIGURE 5. Stress Contours With Differing Adherends.



(b) Shear stress



(c) Normal stress

FIGURE 5 (Cont'd.). Stress Contours With Differing Adherends.

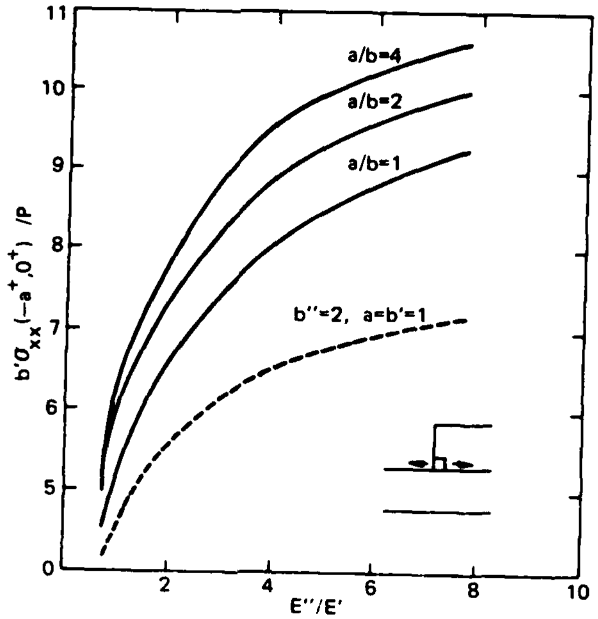
Because of two dimensional effects (strain variations and different traction distributions) near the edges of the joint, the adherends do not act as a single beam of thickness $b' + b''$. Near the joint, significant shear and normal stresses are present in addition to the in-plane component. The shear stresses which transmit the applied load from one adherend to the other are heavily concentrated near the ends of the bondline. This distribution of shear stress on the bondline follows from the equal extensional strain in each adherend across the bondline. Away from the bondline, shear stress decreases (see Figure 5b).

While bondline shear stresses enforce compatibility of extensional strain between the adherends, bondline normal stresses enforce compatibility of normal displacements. Without these tractions the adherends would bend as separate plates within the region of the joint. Near the edges of the joint this bending would result in a separation of the plates, hence the tensile stresses in this region. Since the resultant normal stress on the bondline vanishes, away from the edges, this traction becomes compressive. Distribution of normal stresses throughout the adherends is indicated by the contours in Figure 5c.

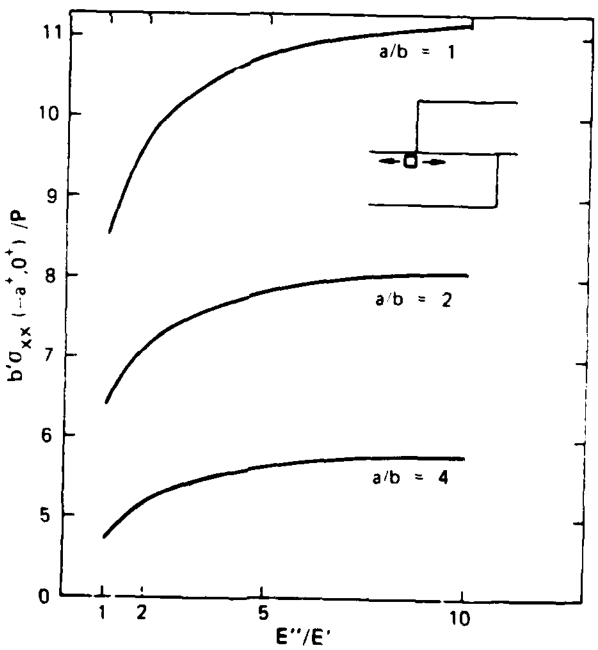
EFFECT OF DISSIMILAR ADHEREND MODULUS ON STRESS CONCENTRATION

The influence of differing elastic moduli on stress components at the end of the stiffer adherend (the largest joint stress concentration) is shown in Figure 6. In the case of shear and normal stress components, these values were obtained by averaging the stresses from the adjacent three elements at this bondline end mode. The in-plane stress, which is generally not continuous across the bondline, was evaluated both in the stiffer adherend and outside the joint in the weaker adherend. In-plane and shear stresses monotonically increase with increasing stiffness of either adherend, while the normal stress decreases for modulus ratios greater than two.

The in-plane stress in the joint increases with elastic modulus because the neutral axis of bending shifts into the higher modulus adherend. Bending stresses on the bondline increase, particularly on the stiffer side of the bondline.[5] The increase in shear stress concentration is associated with the shift in force transmission toward the end of the stiffer adherend.[1] Normal stress maximum values decrease because increasing the modulus of one adherend decreases the bending of that plate. Consequently, a smaller normal traction is required to provide normal displacement compatibility between the plates in comparison with equal modulus adherends.

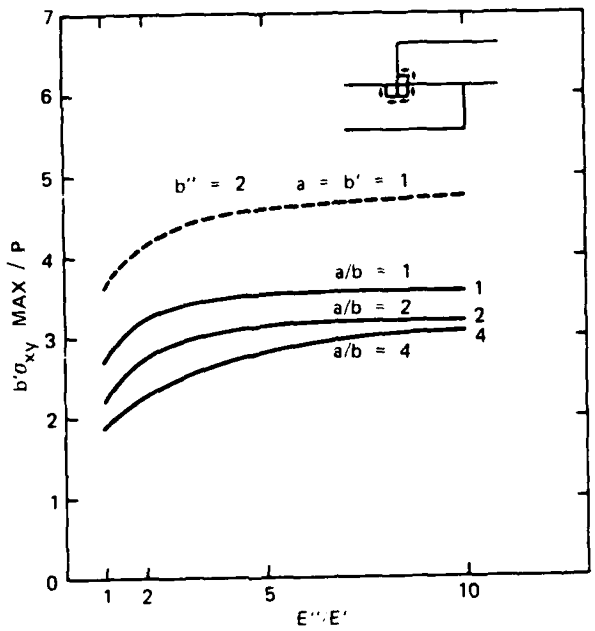


(ai) In-plane; adherend 2

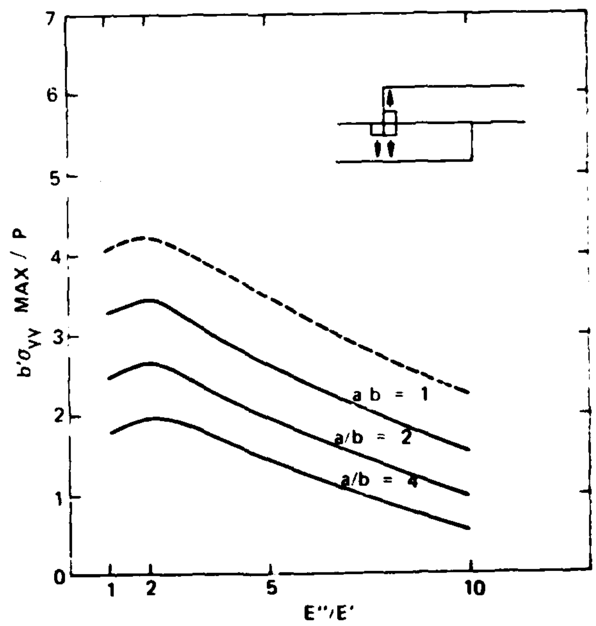


(aii) In-plane; adherend 1

FIGURE 6. Stress Concentration With Differing Elastic Modulus Adherends.



(b) Shear



(c) Normal

FIGURE 6 (Cont'd.). Stress Concentration With Differing Elastic Modulus Adherends.

Increasing adherend overlap distributes bondline stress concentrations more broadly and decreases their magnitude in most cases. Normal stresses are most influenced by overlap length since they are a function of the length of the bending element, a.

EFFECT OF DISSIMILAR ADHEREND THICKNESS ON STRESS CONCENTRATION

The dashed line in Figure 6 shows the effect of doubling the thickness of one plate. The increased offset increases the plate bending moment at the edges of the joint and moves the neutral axis of bending in the joint, off the bondline. These effects increase in-plane stress on the bondline. The thicker plate also has more bending stiffness, but the effect of the increased moment is larger so normal stresses increase in comparison with equal thickness plates. The simple bending analysis (Equation 5) predicts this increase in stress concentration factor to be proportional to $(b' + b'')/2a$, whereas the finite element analysis shows a factor $[(b' + b'')/2a]^{0.8}$.

The largest effect of differing plate thickness is on shear stress. This results from the shift in stress distribution caused by the difference in elongation stiffness of the two plates. This effect is larger than a corresponding difference in elastic modulus. The difference would be less if a joint with larger a/b (more overlap) was considered.

EFFECT OF DISSIMILAR ADHEREND POISSON'S RATIO ON STRESS CONCENTRATION

In Figure 7, stress concentration factors for equal thickness joints with $\nu''/\nu' = 1.5$ (dashed lines) are compared with joints of similar materials (solid lines). These factors are shown as a function of stiffness ratio between the adherends. Shear stresses are unaffected as Sternberg has noted.[5] However, in-plane and normal stress are substantially increased.

A related problem of two, edge-bonded, elastic quarter-planes loaded on the boundary has been solved analytically.[10] There, when both elastic constants of one adherend are larger than those of the other adherend, the effect of Poisson ratio on in-plane stress* decreases as the ratio of

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* The stress component parallel to the bondline.

[10] D. B. Bogy. "Edge-bonded Dissimilar Orthogonal Elastic Wedges Under Normal and Shear Loading," *J. Appl. Mech.*, Vol. 35 (1968), pp. 460-475.

elastic moduli increases. This is evident on the lap joint in-plane stress also (Figure 7). Bondline tearing stress also increases significantly with increased Poisson ratio. The increase in this component is insensitive to differences in the elastic moduli. Increasing incompressibility of the material as Poisson ratio approaches 1/2 is responsible for the change in bondline tearing stress.

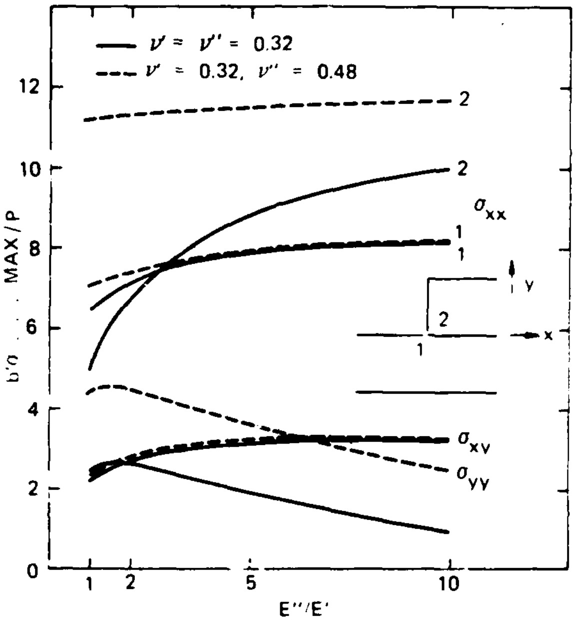

FIGURE 7. Effects of Differing Poisson Ratio on Bondline Stress Concentration Factors.

EFFECT OF ELEMENT SIZE ON STRESS CONCENTRATION FACTORS

In an elastic lap joint, stresses are singular at the ends of the bondline. For a single lap joint of similar adherends bonded to the ends of the overlap region, the theoretical order of this singularity is $r^{-0.56}$ [England].[8] Figure 8 illustrates the dependence of normal stress concentration factor on element size in this model. A least squares fit to these curves yields singularities of order $r^{-0.47}$, $r^{-0.54}$, and $r^{-0.49}$ respectively for elements 1, 2, and 3 around the end of the bondline. This is for a range of element size $50 \leqslant b/\Delta s \leqslant 300$. We conclude that stresses are singular in this model. The observed singularity is less sharp than theoretically expected.

A consequence of this stress singularity is that stress concentration factors for the ends of the bondline have no absolute significance. These extrapolated values are still useful for assessing the influence of various joint parameters.

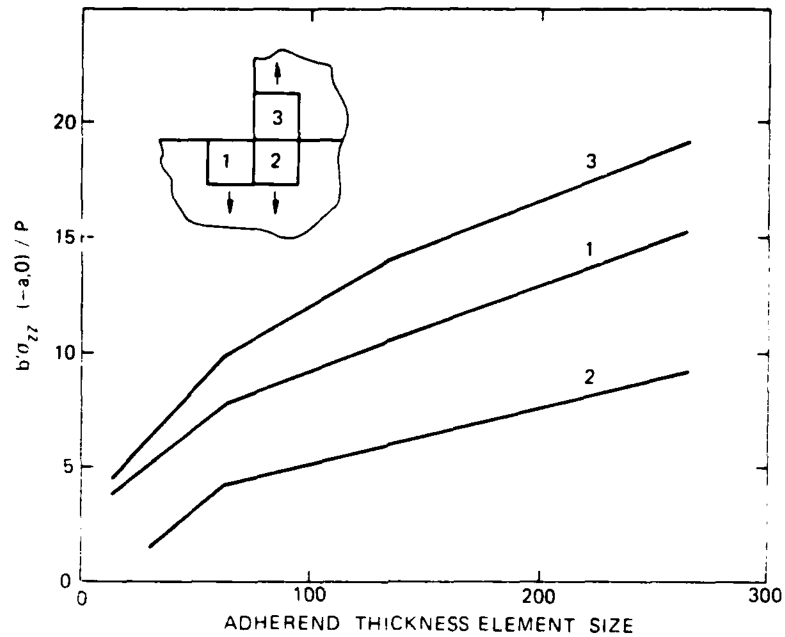

FIGURE 8. Effect of Element Size on Corner Tearing Stress for Similar Adherends.

CONCLUSIONS

The effect of dissimilar adherend materials and geometries on the stresses in structural lap joints has been investigated. With elastic materials, the largest stresses occur as singularities at the ends of the bondline. Stress concentration factors at these singularities have been obtained by extrapolation. The strength of these stress concentration factors has been determined since they are likely points of fracture initiation. Because the finite element method can only yield finite values for stresses in the elements and at the nodal points, the stress concentration factors obtained at the ends of the bondline are not necessarily accurate. Nevertheless, as relative values, these factors accurately reflect the functional dependence of the stresses at the lap joint ends on the material and geometric properties of the lap joint configuration.

The effects of dissimilar adherends is generally to shift the stress distribution toward the end of the stiffer adherend, increasing the stress concentration factor there. Elastic modulus has proportionately less effect on this shift than adherend thickness. Poisson's ratio has the smallest influence on the stress distributions, and this is limited to in-plane and tearing stresses.

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1 Tactical Fighter Weapons Center, Nellis Air Force Base (CC/CV)
12 Defense Technical Information Center
1 Defense Nuclear Agency (Shock Physics Directorate)
1 Weapons Systems Evaluation Group
1 Lewis Research Center
2 Allegany Ballistics Laboratory, Cumberland, MD
2 Applied Physics Laboratory, JHU, Laurel, MD (Document Library)
1 Arthur D. Little, Inc., Cambridge, MA (W. H. Varley)
2 Chemical Propulsion Information Agency, Applied Physics Laboratory, Laurel, MD

1 IIT Research Institute, Chicago, IL (Document Librarian for Department M)
1 Jet Propulsion Laboratory, CIT, Pasadena, CA (Technical Library)
1 Los Alamos Scientific Laboratory, Los Alamos, NM (Reports Library)
1 Princeton University, Forrestal Campus Library, Princeton, NJ
1 Stanford Research Institute, Poulter Laboratories, Menlo Park, CA
1 The Rand Corporation, Santa Monica, CA (Technical Library)
1 University of California, Lawrence Livermore Laboratory, Livermore, CA
1 University of Denver, Denver Research Institute, Denver, CO
1 University of South Florida, Tampa, FL (Dept. of Structures, Materials, and Fluids, W. G. Carpenter)

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